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## worthiness Qualification Criteria for Rotorcraft h External Sling Loads

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20021113 049

Prepared for NASA Ames Research Center  
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## **Airworthiness Qualification Criteria for Rotorcraft With External Sling Loads**

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## TABLE OF CONTENTS

Table of contents.....	i
Summary .....	1
Definitions.....	1
Introduction.....	2
Aeroservoelastic stability.....	3
Definitions of ASE stability and Stability Margins.....	4
Recommended ASE stability criteria.....	8
Pilot task performance - Handling Qualities .....	9
ESL related paragraphs in ADS-33E-PRF .....	9
Recommended HQ criteria .....	10
Load suspension system failures .....	12
Load stability at all speeds.....	13
External load flight envelopes.....	14
Proposed criteria for airworthiness qualification with external sling loads.....	16
Rotorcraft airworthiness qualification ESL off .....	16
Rotorcraft airworthiness qualification ESL on.....	16
Guidance for application of ESL AWQ criteria .....	17
Specific load airworthiness clearance and certification.....	18
References .....	20
Appendix A. Flight test to establish load maneuvering envelope.....	21
Appendix B: ADS-33E-PRF treatment of failures and reliability .....	25
Appendix C: Recommended ESL Handling Qualities design Criteria for Low Speed and Hover in the Degraded Visual Environment.....	27

## SUMMARY

This report presents the results of a study to develop airworthiness requirements for rotorcraft with external sling loads. The report starts with a review of the various phenomena that limit external sling load operations. Specifically discussed are the rotorcraft-load aeroservoelastic stability, load-on handling qualities, effects of automatic flight control system failure, load suspension system failure, and load stability at speed. Based on past experience and treatment of these phenomena, criteria are proposed to form a package for airworthiness qualification. The desired end objective is a set of operational flight envelopes for the rotorcraft with intended loads that can be provided to the user to guide operations in the field. The specific criteria proposed are parts of ADS-33E-PRF, MIL-F-9490D, and MIL-STD-913A all applied in the context of external sling loads. The study was performed for the Directorate of Engineering, US Army Aviation and Missile Command (AMCOM), as part of a contract monitored by the Aeroflightdynamics Directorate, US Army AMCOM.

## DEFINITIONS

AFCS	-Automatic Flight Control System
ASE	-Aeroservoelastic
AWQ	-Airworthiness qualification
db	-Decibels [ $20 \log_{10}$ (output/input)]
DVE	-Degraded Visual Environment as defined in ADS-33E-PRF (see ref 1)
ESL	-External sling load
FCS	-Flight Control System
FDCS	-Flight Data Collection Sheet
Fe	-Equivalent flat plate area
c.g.	-Center of gravity
GVE	-Good Visual Environment as defined in ADS-33E-PRF (see ref 1)
GW	-Gross weight of external load
HQ	-Handling qualities
HQR	-Handling qualities rating
MTE	- Mission Task Element
OFE	-Operational Flight Envelope as defined in ADS-33E-PRF (Ref 1) The envelopes are defined in terms of airspeed, altitude, load factor, rate of climb, side velocity and any other parameters required to define limits.
Q, q	-Dynamic pressure
Se	-Equivalent planform area
SFE	-Service Flight Envelope, as defined in ADS-33E-PRF (Ref 1)
UCE	-Usable Cue Environment, as defined in ADS-33E-PRF (Ref 1)

Configurations	-A rotorcraft configuration is defined by the external geometry. This includes the position of variable systems such as landing gear or flaps, location of external stores, or carriage of sling loads (see Ref 1).
Loadings	-Loadings refers to the mass properties of the rotorcraft configuration and will be reflected in the total mass or weight, the center of gravity location, and the various moments of inertia (see Ref 1).
Load Mass Ratio	- the ratio of the mass of the load to the mass of the helicopter plus load
Settings	-Settings refer to the selected functionality of rotorcraft components or systems that affect rotorcraft response, or Usable Cue Environment (UCE) that can be activated or deactivated by the pilot (see Ref 1).
States	-Rotorcraft states are Normal when the various systems are functioning as selected. Failure states exist when the functionality is modified by one or more malfunctions in rotorcraft components or systems that affect rotorcraft response or UCE (see Ref 1).
ESL configuration	-External sling load configuration includes all the parameters that affect the load external geometry, and include at least the following: Load shape Sling set geometry and material Vertical, longitudinal, and lateral hook location(s) relative to the rotorcraft c.g.
ESL loadings	-External sling load loadings refers to the mass properties of the external sling load and include: Load mass Load c.g. location Load inertia Load distribution between multiple hooks

## INTRODUCTION

The purpose of this report is to define a set of requirements and criteria that must be observed to guide airworthiness certification of rotorcraft for carrying external loads. Many factors influence the safety of flight with External Sling Loads (ESL). These safety factors need to be considered during rotorcraft development. The desired end objective is a set of Operational Flight Envelopes (OFEs) for the rotorcraft when carrying its intended loads that can be provided to the user to guide operations in the field. These OFEs should be related to the internally loaded rotorcraft OFE with addition of ESL parameters as necessary to define the appropriate limits.

Some of the limiting phenomena that will need to be considered when defining the rotorcraft ESL OFE are as follows:

1. Interactions between the flight control system, the helicopter structure, the load, and the pilot, can result in aeroelastic instabilities. The pilot-rotorcraft dynamics must be stable and sufficiently well damped to resist turbulence and to permit accomplishment of tight tracking tasks.

2. At low airspeeds, an external load can swing and coupled helicopter-load responses can introduce motions that cause the pilot difficulty of control especially while performing precision tasks. Such load interactions will be worse with high load mass ratios.
3. Failures in the automatic flight control system (AFCS) can result in unacceptable transients or degraded steady state handling qualities that require load jettison to retain control without damage to the rotorcraft.
4. At any speed, complete failure of one end of a dual point suspension can cause the load to swing into the helicopter, introduce upsetting moments that may be uncontrollable, or induce unsustainable loads on the remaining supports. Similarly, failure of one leg of a multi-leg suspension can result in uncontrollable load motions.
5. As airspeed is increased, the aerodynamic characteristics of the specific load will become important. The aerodynamics can cause the load to trail at an excessive angle, oscillate or rotate about an axis that twists the sling(s), oscillate or swing as a pendulum in pitch and roll, or fly up into the carrying helicopter. Some of these motions can occur suddenly with a violent motion.

With these phenomena in mind, the aeromechanics related considerations for airworthiness qualification (AWQ) of a rotorcraft that has to carry externally slung loads would have to cover the following aspects:

1. Aeroservoelastic stability
2. Pilot task performance- handling qualities
3. Flight control system failures
4. Load suspension system failures
5. Load stability at all speeds

These aspects will be discussed in turn in the following sections. In a subsequent section the essence will be collected together to form a package for guiding AWQ of a rotorcraft to carry externally slung loads, and provide procedures for specific load certification.

## **AEROSERVOELASTIC STABILITY**

Stability analysis needs to deal with both aeroelasticity and aeroservoelasticity. The difference between these two topics is the effect of the flight control system and the pilot closed loop control of the helicopter. Aeroelasticity deals with the mutual interaction of elastic, inertial, and aerodynamic forces. Helicopter aeroelastic stability analysis must be conducted to ensure that no ground or air resonance conditions occur in the coupled rotor-fuselage-drive-landing gear system. These analyses are open loop in the sense that control surfaces remain fixed throughout the stability analyses. Aeroservoelastic (ASE) stability analysis examines the stability of the closed loop system. In a closed loop system the control surfaces deflect in response to control commands, elastic structural deformations at the rotor hub or sensors, and undesired or involuntary pilot inputs (biodynamic feedback). It is very important that any analyses conducted to predict stability include aeroservoelastic effects.

Moving a load from internal to an external sling can modify the ASE characteristics of a rotorcraft, as well as introduce additional modes. On current US Army rotorcraft such as the UH-



60 Black Hawk, and the CH-47 Chinook families, the effects of externally slung loads (ESL) on the ASE characteristics have not been significant. However, some large more flexible rotorcraft, such as the Navy/Marine CH-53 family, or V-22 Osprey, have required extensive tests and analyses to define safe ESL OFE. Both of these rotorcraft have low frequency structural flexibility modes which can interact with those of the external load suspension system. Since these modes are structural, they typically display low damping characteristics. When the frequencies of these modes overlap the active range of the pilot and the flight control system (FCS), unstable coupling is possible and has been experienced operationally. At the other end of the spectrum, small helicopters may encounter limits because of their flight control augmentation or design objectives. For example, the RAH-66 Comanche uses a high gain full authority fly-by-wire FCS to achieve the agility and handling qualities required to perform demanding mission tasks and operations in a degraded visual environment. High FCS gains can lead to low damping or even destabilization of rotor, or rotor-body modes. In addition, the Comanche program has placed heavy emphasis on reducing structural weight. Consequently, the composite structure is tailored for minimum stiffness, which increases the susceptibility of FCS to structural coupling and biodynamic feedback. Upgrades to US Army helicopters usually involve significant increases in gross weight and some re-tuning of the AFCS feedback gains, both of which have the potential for ASE stability margin reductions. These factors suggest that during development of all future rotorcraft intended to carry ESL, whether major upgrades or entirely new systems, the ASE stability margins determined with internal loading should be rechecked when carrying ESL.

## **Definitions of ASE stability and Stability Margins**

There are at least two definitions of ASE stability requirements for flight control systems that may be applied to ESL; these are MIL-C-18244A and MIL-F-9490D.

### **MIL-C-18244A**

MIL-C-18244A (Ref. 2) is a military specification for automatic control and stabilization systems for piloted aircraft. It was developed in 1955 and revised in 1962. The pertinent requirement paragraphs are:

#### **3.1.1.6.1 Stability Margins**

The AFCS shall be demonstrated to be stable in all modes of operation in all flight conditions as follows: All AFCS aerodynamic loops shall be flight demonstrated to be stable for at least one and one half times the production gain. At the beginning of service life and under standard conditions as specified in Specification MIL-E-5272, all AFCS non-aerodynamic servo loops shall be demonstrated to be stable at three times the production gain. All AFCS non-aerodynamic loops shall be demonstrated to be stable at one and one-half times the production gain throughout all operating service conditions. At the end of service life, and under standard conditions, all non-aerodynamic loops shall be demonstrated to be stable at one and one half times the production gain. It shall also be demonstrated that an additional lag of 45 degrees, when introduced into any loop with production gains, shall not result in instability.

## MIL-F-9490D

A more modern set of criteria for control system design is given in MIL-F-9490D, Ref 3. The pertinent paragraphs in this document are:

### 3.1.3.6 Stability

For FCS using feedback systems, the stability as specified in 3.1.3.6.1 shall be provided. Alternatively, when approved by the procuring activity, the stability defined by the contractor through the sensitivity analyses of 3.1.3.6.2 shall be provided. Where analysis is used to demonstrate compliance with these stability requirements, the effects of major system nonlinearities shall be included.

#### 3.1.3.6.1 Stability margins

Required gain and phase margins about nominal are defined in Table III for all aerodynamically closed loop FCS. With these gain or phase variations included, no oscillatory instabilities shall exist with amplitudes greater than those allowed for residual oscillations in 3.1.3.8, and any nonoscillatory divergence of the aircraft shall remain within the applicable limits of MIL-F-8785 or MIL-F-83300 or *ADS-33E-PRF (added for rotorcraft)*. AFCS loops shall be stable with these gain or phase variations included for any amplitudes greater than those allowed for residual oscillations in 3.1.3.8. In multiple loop systems, variations shall be made with all gain and phase values in the feedback paths held at nominal values except for the path under investigation. A path is defined to include those elements connecting a sensor to a force or moment producer. For both aerodynamic and nonaerodynamic closed loops, at least 6 db gain margin shall exist at zero airspeed. At the end of system wear tests, at least 4.5 db gain margin shall exist for all loops at zero airspeed. The margins specified by Table III shall be maintained under flight conditions of most adverse center-of-gravity, mass distribution, and external store configuration throughout the operational envelope and during ground operations.

Table III: Gain and phase margin requirements (db, deg.)

Mode frequency	Airspeed			
	Below $V_{oMIN}$	$V_{oMIN}$ to $V_{oMAX}$	At $V_L$	At 1.5 $V_L$
$f_M > 0.06$ Hz	GM = 6 db No phase requirement below $V_{oMIN}$	GM = $\pm 4.5$ PM = $\pm 30$	GM = $\pm 3.0$ PM = $\pm 20$	GM = 0 PM = 0 Stable at nominal phase and gain
$0.06 < f_M$ <first aeroelastic mode		GM = $\pm 6.0$ PM = $\pm 45$	GM = $\pm 4.5$ PM = $\pm 30$	
$f_M >$ first aeroelastic mode		GM = $\pm 8.0$ PM = $\pm 60$	GM = $\pm 6.0$ PM = $\pm 45$	

$V_L$	= Limit Airspeed (MIL-A-8860).
$V_{oMIN}$	= Minimum Operational Airspeed (MIL-F-8785).
$V_{oMAX}$	= Maximum Operational Airspeed (MIL-F-8785).
Mode	= A characteristic aeroelastic response of the aircraft as described by an aeroelastic characteristic root of the coupled aircraft/FCS dynamic equation-of-motion.
GM	= Gain Margin (db). The minimum change in loop gain, at nominal phase, which results in an instability beyond that allowed as a residual oscillation.
PM	= Phase Margin (deg). The minimum change in phase at nominal loop gain which results in an instability.
$f_M$	= Mode frequency in Hz (FCS engaged).
Nominal Phase and Gain	= The contractor's best estimate or measurement of FCS and aircraft phase and gain characteristics available at the time of requirement verification.

#### 3.1.3.6.2 Sensitivity analysis

Tolerances on feedback gain and phase shall be established at the system level based on the anticipated range of gain and phase errors which will exist between nominal test values or predictions and in-service operation due to such factors as poorly defined nonlinear and higher order dynamics, anticipated manufacturing tolerances, aging, wear, maintenance, and noncritical material failures. Gain and phase margins shall be defined, based on these tolerances, which will assure satisfactory operation in fleet usage. These gain and phase tolerances shall be established based on variations in system characteristics either anticipated or allowed by component or subsystem specification. The contractor shall establish, with the approval of the procuring agency, the range of variation to be considered based on a selected probability of exceedance for each type of variation. The contractor shall select the exceedance probability based on the criticality of the flight control function being provided. The stability requirements established through this sensitivity analysis shall not be less than 50 percent of the magnitude and phase requirements of 3.1.3.6.1.

#### Current situation

Both of these criteria have been used to investigate ASE stability margins in helicopters. The former criteria, MIL-E-18244A, was used by Sikorsky on a task for the Navy to develop MH-53C safe operating envelopes for externally slung loads of 25,000 lb with dual suspension. The latter, MIL-F-9490D, has been used by Bell-Boeing on the V-22, for both internal loadings and for the ESL flight envelopes. MIL-F-9490D has also been used by Boeing-Sikorsky on the Comanche, for flight envelope development with internal loading.

The Comanche originally had a requirement for sling load capability, and required clearance to MIL-F-9490D with external loads. The ESL capability has since been deleted, but the standards of MIL-F-9490D were applied to the internal loading. The pertinent analysis is described in Ref 4. MIL-F-9490D requires that the gain and phase stability margins be achieved at the most

adverse center-of-gravity, mass distribution, and external store configuration throughout the operational envelope and during ground operations. To determine the most adverse conditions, the Comanche analysis sorted through three gross weights with the retractable weapons carriers open and closed, at two sets of ambient conditions, for each of the three primary sets of control laws, and the full range of airspeeds. The ASE model developed included elastic airframe modes, control laws, sensor and actuator dynamics, and drive system dynamics. In addition, a pilot model was added to investigate the potential effects of biodynamic feedback. This pilot model represented the pilot system structure, seat cushion, and pilot mass as well as the flight control task closures. The frequency range considered went beyond the flight control actuators' bandwidths of 13 Hz to include the primary rotor modes and flexible structural modes to 20 Hz. The Comanche analysis was updated with flight data before AFCS loops were closed during envelope expansion flight tests. Safety was assured, though some further tailoring has been

required to reduce nuisance couplings to acceptable levels.

On the MH-53C, Sikorsky performed flight test with dense loads and used the data to refine and validate a math model of the helicopter (Ref 5). The math model was subsequently used to define envelopes with other load shapes. This effort was an extension of a previous program to develop an ESL math model for both the CH-53E and the UH-60L described in Ref 6.

It is instructive to analyze the MH-53C data in Ref 5 to see how changing the loading from internal to external, and the external from single point to dual point suspension can affect the ASE stability margins. The roll axis had the smallest, and in some cases limiting, ASE stability margins so only that axis will be shown. Figure 1 shows the MIL-E-18244A and MIL-F-9490D boundaries plotted versus frequency. The change in requirement occurs at the first aeroelastic mode which in this case is the rotor lag regressive mode at

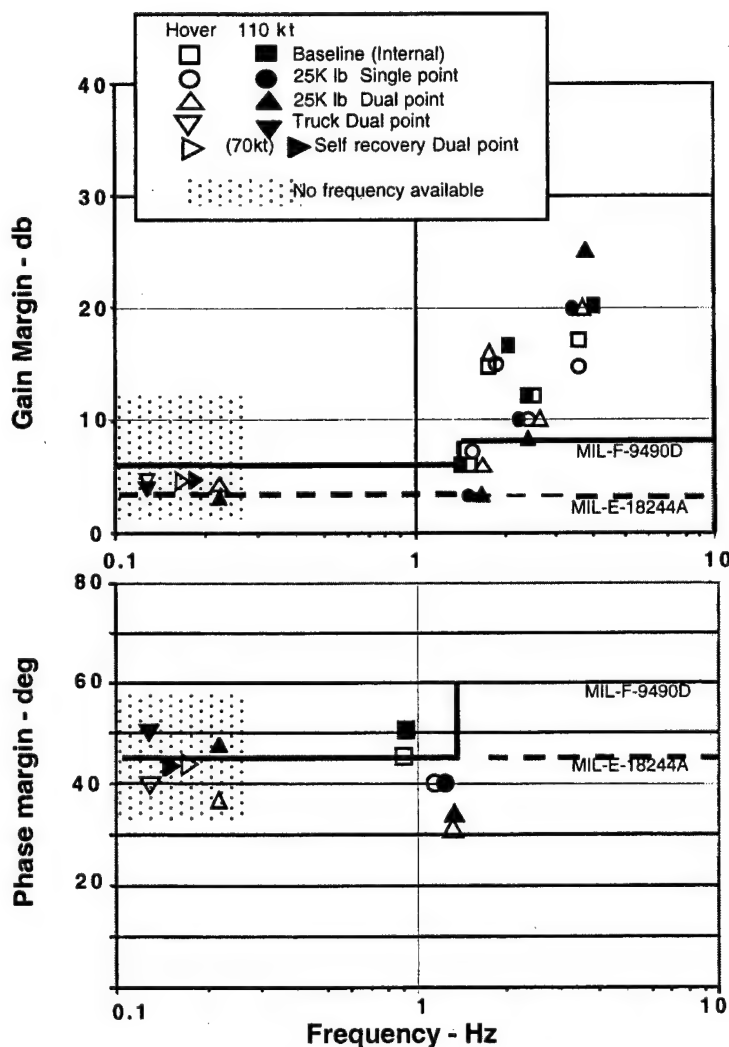


Figure 1: Effect of speed and load configuration on MH-53C gain and phase margins

about 1.4 Hz. Comparing the results for the range of loads and two speeds, the following points are notable:

1. As airspeed is increased the gain margins got slightly worse (reduced) whereas the phase margins improved. Though small, these effects can be quite important in the critical regions near the stability boundaries.
2. At both hover and 110 kt, as the load is changed from internal to external dense (concrete/steel block with minimal aerodynamics) with single point suspension to external dense (steel sled with minimal aerodynamics) with dual point suspension there is little change in the gain margins but a significant reduction in the phase margins.
3. Changing the dual point suspension load from dense, to medium density (truck, with aerodynamics) to low density (CH-53E with full fuselage aerodynamics, defined as self recovery) had only a small effect on the closed loop stability. Analysis of the self recovery configuration was limited to 70 kt for reasons other than ASE stability. It should be noted that the results for these medium and low density loads are based on Sikorsky predictions using the validated GenHel math model and models of the load. The report does not include frequency sweep data or associated frequencies for these cases. It is likely that they occurred around 1.5 to 2.0 Hz, but have been plotted in a region noted as "no frequency available". For consistency when making comparisons, the predicted values for the dual point suspension dense load are also plotted in the same region.

The three dual point suspension loads had the same mass (25,000 lb), but widely different moments of inertia and aerodynamics. A range of hook loadings was also investigated and changing the load distribution between the forward and aft hooks in the range of 70/30 to 30/70 had a minor effect on the ASE stability margins. This was true for all of the 25,000 lb dual point suspension loads except that the dual point truck showed decreased gain margin as the load was reduced on the forward hook.

On the basis of these tests and simulation model analyses Sikorsky defined a loading envelope for the MH-53E having a format similar to that for the V-22 shown in Figure 2. Added to this loading flight envelope is the requirement to stay within the basic MH-53E c.g. envelope and to observe airspeed limitations of 90 kt for maximum and medium density ESL and 70 kt for low density ESL.

These results suggest that at least for the MH-53C, the closed loop ASE stability margins determined using a defined sling set and generic dense loads, plus selected low and medium density loads, can give a good indication of the likely stability margins. The resulting envelopes will encompass the outer limits of the operating envelope. As discussed later, other factors will probably impose further restrictions on the flight envelopes for specific loads.

## **Recommended ASE stability criteria**

Though the MH-53E was assessed with respect to the MIL-E-18244A, the US Navy requires application of the MIL-9490D standards for ASE stability margins in new designs. This would be especially the case for aircraft with complex flexible structures (such as the V-22) or fly-by-

wire flight control systems (such as the V-22 and RAH-66) or high gain flight control augmentation systems (such as V-22, RAH-66). The choice of criteria to apply to upgrades of existing fleet helicopters that were designed before the need for explicit consideration of ESL ASE stability is a more complex question. On the one hand, they have demonstrated many years of successful operation that suggests that they have adequate ASE stability. On the other hand, upgrades often involve increasing the rotorcraft gross weight, expanding the load carrying envelopes, and improving the flight control system augmentation. Recent examples are the MH-53E, CH-47F, UH-60M, and UH-60X. Such enhancements put more demands on the structure and the flight control system. ASE stability margins can be reduced, and the stability margins could become limiting factors in the enhancements. As a result, it may be necessary to trade desired enhancements such as improved handling qualities with the need to maintain ASE stability margins. So again it is recommended that the Navy's example be followed and require demonstration of ASE stability versus MIL-F-9490D, not just for new designs, but for upgrades as well. If the "old" design cannot achieve these limits without major degradation in handling qualities, be flexible and allow the ASE stability margins to degrade towards MIL-E-18244A. In this case, it is important to realize that the rotorcraft will be particularly sensitive to load modifications. Thus, it will be necessary to perform checks with specific loads to ensure that the vehicle is safe, though perhaps subject to minor vibrations during unusual levels of control aggressiveness or in turbulence.

## **PILOT TASK PERFORMANCE - HANDLING QUALITIES**

Handling qualities requirements for Army rotorcraft are currently defined by Aeronautical Design Standard ADS-33E-PRF, Performance Specification, Handling Qualities Requirements for Military Rotorcraft (Ref 1). This performance specification provides a comprehensive set of criteria for the HQ of rotorcraft with internal loading. The coverage for rotorcraft with ESL is much more limited. The following are the pertinent paragraphs from sections 3.0 Requirements and 4.0 Verification. Included in ADS-33E-PRF are requirements on the treatment of ESL suspension system failures and load jettison. These topics are included below for completeness, and to explain the context in which they are to be applied.

### **ESL related paragraphs in ADS-33E-PRF**

#### **3.1.5.2 Assigned Levels of handling qualities**

To determine the Assigned Level of handling qualities, test pilots shall use the Cooper-Harper Handling Qualities Rating (HQR) Scale (Figure 1 of Ref 1) to assess the workload and task performance required to perform the designated MTEs. For the assigned Level of handling qualities to be Level 1, the rotorcraft shall be rated Level 1 for all of the MTEs designated as appropriate to the rotorcraft's operational requirements. With an externally slung load in DVE, the HQRs shall be Level 1 for load mass ratios (6.2.8) less than 0.25, and shall not degrade to worse than 4.0 for load mass ratios up to 0.33. The Government shall judge the acceptability of any degradations when performing a MTE in moderate wind, and with load mass ratios greater than 0.33.



### **3.10 Requirements for externally slung loads**

#### **3.10.1 Load release**

The rotorcraft shall be capable of safely jettisoning external loads from any condition within the External Loads Service Flight Envelope.

#### **3.10.2 Failure of external load system**

Within the External Loads Service Flight Envelope, any single failure of a suspension system element (including attachment fittings, slings, pendants, apex fittings, and cargo hooks) shall not result in loss of control of the rotorcraft or cause substantial damage to the airframe. When crew members have the capability to monitor and jettison the load in a fully attended manner, a 1.0 second failure recognition delay time shall be considered when evaluating crew initiated jettison scenarios.

### **3.11 Mission Task Elements to be performed with ESL (GVE and DVE)**

#### **3.11.1 Hover**

#### **3.11.6 Vertical maneuver**

#### **3.11.7 Depart/Abort**

#### **3.11.8 Lateral reposition**

### **4.3 Testing with externally slung loads**

Testing of applicable MTEs with externally slung loads shall be accomplished with a load mass ratio (6.2.8) of 0.33, or the maximum load that will be used for operational missions, whichever is less. If load mass ratios of greater than 0.33 will be used operationally, a configuration with the maximum load mass shall also be tested. The government will decide if HQR degradations at high load mass ratios are acceptable. Testing shall be accomplished in both GVE and DVE if required by 3.1.1.

## **Recommended HQ criteria**

For rotorcraft required to carry ESL it is recommended that the ADS-33E-PRF criteria be applied as follows:

### **Rotorcraft HQ load off**

The rotorcraft shall meet all the requirements of ADS-33E-PRF with ESL off.

This is stated in ADS-33E-PRF, section 6.3.40, but section 6.0 contains Notes, not Requirements, hence the specific statement here.

### **Rotorcraft HQ ESL on**

The rotorcraft shall meet the requirements of ADS-33E-PRF that specifically address ESL (see above). The following additions and interpretations shall be included.

Quantitative criteria to provide a basis for a Predicted Level of handling qualities with ESL on were not available at the time ADS-33E-PRF was published, but have subsequently been completed. The criteria development is described in Ref 7 and the actual criteria are summarized in Appendix C. Although they have not yet been formally adopted, use of these criteria is recommended for design guidance.

The ADS-33E-PRF MTEs listed above provide a basis for qualitatively assessing the HQ and obtaining an Assigned Level of HQ with ESL on. However they only cover hover and low speed

flight. The load stability and maneuverability limitations must be established through the entire speed range. To accomplish this, a version of the tests defined in MIL-STD-913A (Ref 8) shall be used. These tests were developed and are used by the US Army Natick RDEC as part of their load certification process. The slightly modified version to be adopted for ESL AWQ testing is provided in Appendix A.

#### **Rotorcraft failures, ESL on**

ADS-33E-PRF paragraph 3.10.2 requires a 1.0 sec delay for initiating crew action following failures when crew members have the capability to monitor and jettison the load in a fully attended manner. To this should be added a 3.0 second failure recognition delay time for situations when the load is not being monitored in a fully attended manner. This can be done as follows:

##### 3.10.2.a Failure of external load, unattended.

*Failure recognition delay time for situations when the load is not being monitored in a fully attended manner shall be 3.0 seconds.*

There is a need for explicit coverage of FCS failures ESL on. FCS failures that are innocuous ESL off may be uncontrollable ESL on, or result in dangerous load motions, or the aircraft load combination may be unflyable in the steady state following the FCS failure. Both of these eventualities can be addressed by applying the ADS-33E-PRF failure philosophy to the rotorcraft-ESL combination. This can be accomplished by adding the following paragraph to those called out in ADS-33E-PRF:

##### 3.10.3 Rotorcraft failures while carrying ESL

*The requirements of 3.1.14 shall apply with ESL on.*

The pertinent paragraphs 3.1.14 are provided in Appendix B and shall be interpreted as follows:

#### **Failures and reliability**

##### 3.1.14.1 Allowable Levels based on probability.

Use the table of failure states generated for the basic internally loaded rotorcraft, but assess the degree of HQ degradation, both transient and steady state, with the ESL in place. These degradations may be different from the degradations load off. If the load had no effect on the HQ following a failure, then so far as failures are concerned, the ESL load-on OFE would be unchanged from the load off envelope. Conversely, if there are parts of the OFE where the ESL causes HQ degradation to Level 2, with failures that occur more frequently than  $2.5 \times 10^{-3}$  per flight hour, then the OFE must be reduced to eliminate those parts.

#### **Specific failures**

##### 3.10.2 Failure of external load system

The failures called out in 3.10.2 Failure of external load system, are specific failures that must be added to the list of specific failures designated for the internally loaded rotorcraft. According to 3.1.14.2, the allowable Level of flying qualities for each Specific Failure will be specified by the procuring activity. 3.10.2 incorporates the requirement that any single failure of a suspension system element shall not result in loss of control of the rotorcraft or cause substantial damage to the airframe. This corresponds to HQ no worse than Level 3.



## LOAD SUSPENSION SYSTEM FAILURES

The previous section provided criteria that shall be met in the event of failures. It is not possible to discuss specific failures since they will depend on the configuration under test. Instead, to provide some insight this section will discuss some of the failure types that could occur, and what the resulting motions of the load may be.

The consideration of failures divides into groups illustrated by the following Table I

*Table I: Considerations for failure types*

Load suspension system	Failure type	
	Complete suspension point failure	Partial suspension point failure
Single point suspension, single load (One hook, one load)	Clean separation and no entanglement of empty cables	Manual release if resulting load or rotorcraft motions become dangerous
Single point suspension, multiple loads (Multiple loads on one or more hooks)		
Multiple single point suspension single loads (Multiple hooks, one load on each)	Clean separation and no hang-up on the retained loads	
Multi point suspension, single load (Two or more hooks, one load)	Jettison before the remaining suspension becomes overloaded.	

### Single-point suspension with single load

With loads suspended on a single hook, the primary safety concern in complete sling failure is to ensure clean separation of the load, and avoid subsequent contact between the rotorcraft and any remains of the unloaded sling. Following partial failure of a redundant suspension system, such as one leg of a multi-legged sling, the load may take up new attitudes relative to the flight path and result in motions that could become dangerous. If the motions were growing faster than the pilot could reduce airspeed the crew chief would have to make a manual release.

### Single-point suspension with multiple loads

With several loads suspended from each of one or more hooks, the primary safety concern in complete suspension failure is to ensure that the loads do not get entangled with the loads on other hooks. As with the single point suspension with single load, following partial failure of a redundant suspension system, the crew chief may have to make a manual release.

### Multiple single-point suspension single loads

If single point loads are to be carried on multiple hooks, it must be possible to release one load at a time. Any dual point auto jettison system that relies on zero load as a safety release signal would have to be inactivated in this situation, or it would sense the released load as a failure, and jettison the load on the other hook.

### Multi-point suspension with single load

With loads suspended on multiple hooks (usually two), complete failure of the fore or aft support will result in the load swinging down until it is restrained by the remaining support(s). At low airspeeds this will induce upsetting moments and structural loads that must be overcome by the rotorcraft or the load released. At high speeds the swing down can be accelerated by the

aerodynamic forces on the load and result in shock loads on the remaining supports as great as five or six times the static values (Ref 9). Such whip loads are most likely to occur with low density loads having a large planform area such as an empty Milvan. It may require automatic jettison to prevent structural damage in such cases. The load envelopes must take this into account. When designing the auto jettison device for the V-22 tilt rotor Boeing found that considerable care is required to provide reliable identification of the suspension system failures while minimizing the risk of false failure identification (Ref 9). Specifically, the trade is between rapid release, which may respond by jettison in an unwanted situation such as in turbulence or aggressive maneuvering, and release that is too slow to prevent the shock load from reaching the remaining hook.

When redundant load paths exist to multiple hooks, failure of only one path will not cause a complete loss of load at one of the hooks. Without such a clear signal, leg failure will be very difficult or impossible to protect with an auto jettison system. Fortunately, in such situations, load motions may take several seconds to build to dangerous levels, thus allowing the crew chief time to recognize the problem and jettison the load. In determining clearance for this case a time delay must be allowed to represent the time taken for the crew that is monitoring the load to recognize the problem and take action. In ADS-33E-PRF this is recognized by requiring at least 1.0 or 3.0 seconds delay in any release test (see previous section).

## **LOAD STABILITY AT ALL SPEEDS**

As airspeed is increased, the aerodynamic drag will cause the loads to float back or trail at an increasing angle. This angle will be proportional to the load drag and inversely proportional to its weight. It is relatively easy to predict this trail angle and set appropriate limits. At some airspeed, most loads will develop a lateral-directional oscillation. This can cause the load to oscillate or rotate about an axis that twists the sling(s), oscillate or swing as a pendulum in pitch and roll, or fly up into the carrying helicopter. Some of these motions can occur suddenly with a violent motion. Such motions are difficult to predict and evaluate in simulation, so are a primary reason for flight testing specific loads to determine their maximum speed and maneuvering envelope. Testing for this envelope has been accomplished for all US Department of Defense rotorcraft by the US Army Natick RDEC in accordance with its interpretation of the mission assignment provided in Ref 10.

For flight testing, the US Army Natick RDEC assumes that the helicopter is airworthy and cleared to carry the load. Natick does not develop the rotorcraft's loading envelope, consider ASE stability, or allow for suspension system failures and jettison limits. All such considerations must be assured and provided by the rotorcraft developer.

In the past, this assurance of airworthiness has been done for US Army helicopters (for example for the UH-60 and CH-47 families) by providing a loading envelope (permissible hook loads and c.g. ranges) and a maneuvering envelope (bank angle versus speed and gross weight).

Development of these envelopes included little consideration of ASE stability or auto jettison. Within these basic envelopes, airspeed limitations were defined for Milvan type loads at various weights, and for high density loads at various weights. This has worked fine for the CH-47 and UH-60 helicopters, but as discussed in the section on ASE stability, the larger and structurally

more flexible CH-53 family ran into problems. As a result, the US Navy has required specific ASE stability testing and consideration of different load types. The V-22 is currently the most complex example of what can be involved in developing ESL clearances. Not only does it have extreme structural flexibility, but also has a high gain full authority fly-by-wire flight control system, and perhaps most important of all, it is capable of very high speeds which the user wants to exploit with ESL. Bell-Boeing have done a considerable amount of work in developing the V-22 ESL clearances and so this rotorcraft will be used as an example of what the US Army may require in the future.

## **External load flight envelopes**

The paper by Miller, et al Ref 9 summarizes the V-22 ESL envelopes developed by Bell-Boeing that resulted from consideration of all the factors that have been discussed above, including:

- Loadings for single and dual suspension loads
- Load geometric trim
- Load behavior following suspension system failures
- Load stability at speed.
- Allowable structural drag loads
- ASE stability
- Handling qualities
- AFCS failures

Envelopes from Ref 9 are reproduced as Figures 2 and 3.

Figure 2 shows the structural external load flight envelope. The V-22 has two hooks and can accommodate single or dual point loads. Figure 2 shows that the maximum single point load is 10,000 lb on either hook, and dual point loads up to 15,000 lb can be shared 70/30 on either hook (except for the 67/33 corner observing the 10,000 lb hook limit).

The limiting behavior of loads primarily depends on:

- Suspension system geometry and sling material
- Load mass
- Load density and shape

Since there are many possible combinations of these three parameters, it is a massive undertaking to address all the possibilities explicitly, even if simulation is used. Flight testing every case would be impossible. Ideally the developer will follow Boeing's V-22 example and

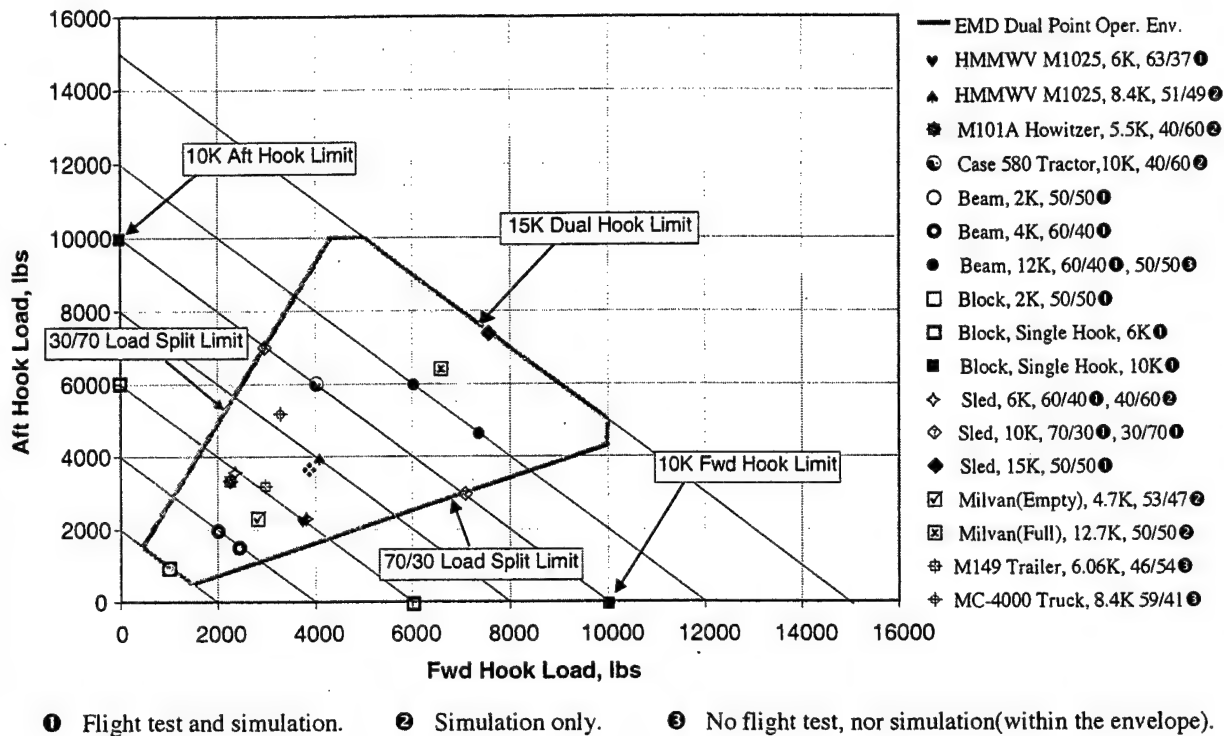


Figure 2. V-22 Structural External Load Flight Envelope (From Ref 9. Copyright The Boeing Company)

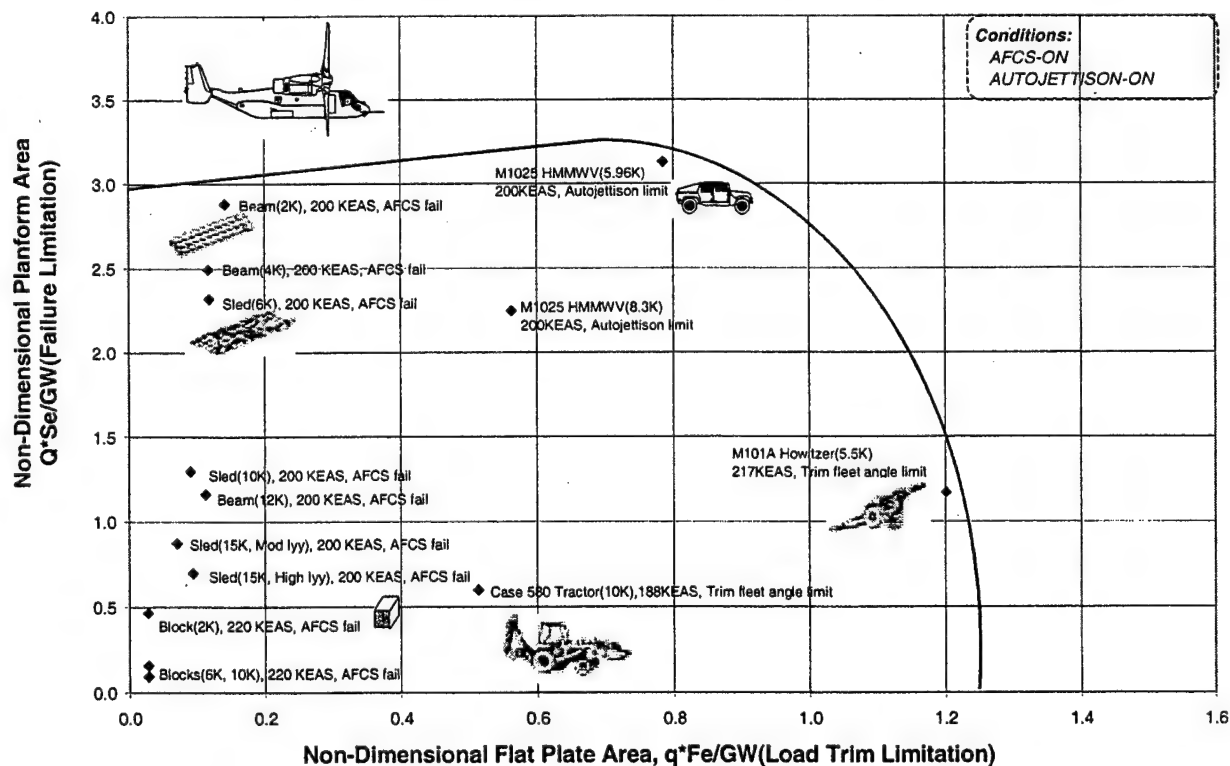


Figure 3. V-22 Aerodynamic External Load Flight Envelope (From Ref 9. Copyright The Boeing Company)

use a combination of simulation and flight test to develop envelopes for a representative set and generate a generic envelope or envelopes.

Consider just the two characteristics, load trim, and load behavior following a suspension system failure. Load trim angle is directly proportional to the drag/weight ratio. The most critical loads for suspension system failure have a relatively small frontal area and low drag, but a large planform or side area. The low drag allows them to be carried at high speed, and the large planform or side area will generate large aerodynamic forces when the load angle of attack or sideslip is perturbed. These two characteristics have been parameterized by Boeing to form the axes in Figure 3. The generic boundary was determined to be as indicated by the solid line. However, as can be seen from the individual data points, other considerations can result in limits that are well inside this basic boundary. This implies detailed testing of many specific loads or groups of loads will be required for airworthiness clearance. The use of piloted simulation and analyses provides insight that can significantly reduce the flight testing required. Critical loads and failures can be identified and flight tests focussed on these cases. Fortunately, all of the V-22 limiting cases are at higher speeds than any helicopter is likely to achieve, so it should be possible to achieve some simplification in load testing for helicopter applications.

## **PROPOSED CRITERIA FOR AIRWORTHINESS QUALIFICATION WITH EXTERNAL SLING LOADS**

Based on the forgoing discussions, the following is a collection of the recommended criteria to be applied to AWQ of rotorcraft with ESL:

### **Rotorcraft airworthiness qualification ESL off**

The ASE stability paragraphs of MIL-F-9490D and all of ADS-33E-PRF apply to the rotorcraft ESL off.

### **Rotorcraft airworthiness qualification ESL on**

The contractor shall define the rotorcraft loadings, ESL loadings and ESL flight envelopes for ESL configurations and rotorcraft states that satisfy the following AWQ criteria:

#### **1. Closed loop ASE stability**

##### **MIL-F-9490D paragraphs:**

- 3.1.3.6 Stability
- 3.1.3.6.1 Stability margins.
- 3.1.3.6.2 Sensitivity analysis.

#### **2. Handling qualities**

##### **ADS-33E-PRF paragraphs:**

- 3.1.5 Levels of handling qualities
- 3.1.14 Rotorcraft failures
- 3.10 Requirements for externally slung loads
- 3.10.1 Load release
- 3.10.2 Failure of external load system

3.10.2.a Failure of external load, unattended. *(New paragraph) Failure recognition delay time for situations when the load is not being monitored in a fully attended manner shall be 3.0 seconds.*

3.10.3 Rotorcraft failures while carrying ESL *(New paragraph). The requirements of 3.1.14 shall apply with ESL on.*

### 3.11 Mission Task Elements

3.11.1 Hover

3.11.6 Vertical maneuver

3.11.7 Depart/Abort

3.11.8 Lateral reposition

4.3 Testing with externally slung loads

### Appendix C of this report:

Recommended ESL Handling Qualities Design Criteria for Low Speed and Hover in the DVE.

### 3. Load maneuvering envelope

#### MIL-STD-913A paragraph:

5.3 Flight testing. *Modified in accordance with Appendix A of this report.*

### GUIDANCE FOR APPLICATION OF ESL AWQ CRITERIA

The current regulations require that each load be certified in accordance with MIL-STD-913A, so as indicated above, the related flight test could be used to define the load maneuvering envelope and provide an overall check on the airworthiness. This leaves the question of how to ensure compliance with the closed loop stability and handling qualities requirements. It would be enormously expensive and time consuming for the rotorcraft developer to show compliance by flight testing every load that will be carried by the rotorcraft. Instead, it is hoped that a mix of analysis, piloted simulation, and flight test can be used. Airworthiness will be influenced by the specific load characteristics, but it may be possible to define OFE with generic loads supplemented by limited testing of specific loads. Such generic loads must adequately represent the critical aerodynamic and inertial characteristics of the range of specific loads that the rotorcraft will be expected to carry.

It is impossible to state in general terms the extent to which modeling and simulation can supplement flight test, or the extent to which generic OFE can be relied upon to assure airworthiness without actually testing each specific load. Modeling and simulation that has been shown to accurately predict flight test results may be used to interpolate or even extrapolate to other situations. Similarly, rotorcraft that demonstrate adequate stability margins that vary little with a wide range of loads may be able to rely on OFE developed with generic loads. This has of course been the situation with the UH-60 and CH-47 families, but less so with the CH-53. Each rotorcraft will have to be judged on its own merits. The following provides some general observations on the current fidelity achievable in modeling and simulation.

Analysis and simulation have been used to support ESL AWQ by both Sikorsky (Ref 6), and Boeing (Ref 9). The MH-53E external cargo assessment program described in Ref 5, started with generic load flight tests to refine and validate a simulation math model originally developed during

the program described in Ref 6. Based on the refined model, and flight tests with a 25,000 lb. dense generic load, the OFE for the 25,000 lb. truck and the self recovery loads were established using only analysis. The process followed the methodology described in Ref 6. Boeing took the process of using simulation one step further by integrating the math model into a piloted flight simulation facility (Ref 9). Use of these capabilities made significant contributions to the V-22 ESL envelope definition. It facilitated estimation of stability limits, investigation of load-on handling qualities, and assessment of flight control augmentation system failures and load suspension system failures. Most of these failures would have been too dangerous to flight test, and the flight testing that had to be performed was made more efficient by identifying the critical loads and conditions.

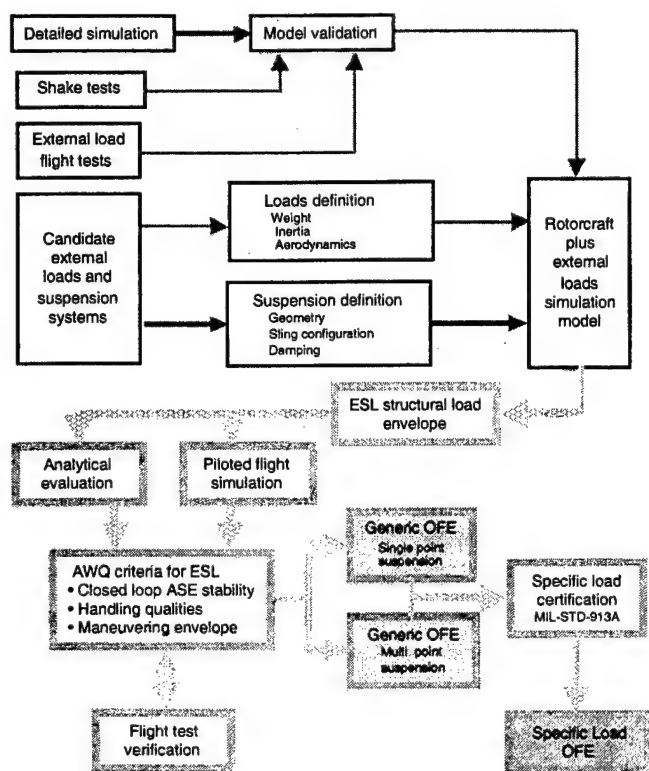
Despite the unquestioned value of simulation and analysis in aiding ESL AWQ, the current state of technology has limitations that make flight verification essential. One continuing limitation of analysis or simulation is the inability to predict reliably the onset of load instability as speed is increased. Two recent Army/NASA projects at the Ames Research Center have been oriented at this problem. The first (Ref 11) demonstrated techniques to make stability predictions from telemetered flight data almost as soon as the test input was over. This allows a rapid and confident move to the next speed condition and thus should minimize flight test time. The second effort (Ref 12) addressed math model fidelity by improving the rotor wake model and the load aerodynamics. Results showed that when using only a static model of load aerodynamics for a simple CONEX box the stability margins could be up to 10 db different from flight, and prediction of the basic pendulum mode damping varied considerably with the aerodynamic model used. Efforts towards developing a dynamic model of load aerodynamics are still underway.

Piloted simulation also suffers from math modeling deficiencies and has additional difficulties in achieving accurate estimates of HQ because of limited motion and visual cueing. Motion cues are particularly important in ESL assessment because the pilot's primary cue of load behavior is the load's effect on motion of the rotorcraft. Boeing compensated somewhat for lack of motion cues by providing the pilot an outside observer's view of the load. This did not cue the rotorcraft motion in response to the load but did show if the load was swinging. For hover and low speed tasks such as the ADS-33E-PRF MTEs, simulator visual cues tend to be deficient compared with good day visibility (GVE). Thus, a Rate response-type configuration known to be Level 1 with an ESL in GVE can produce Level 2-3 ratings on the simulator. In several piloted simulations on the NASA Ames VMS (e.g. Ref 7) it has been found that using an attitude-command-attitude-hold plus height-hold (ACAH+HH) flight control system can essentially compensate for the degraded stabilization cues in the visual scene. In that context, if it is required to carry ESL in the DVE, the simulation results may be reasonably accurate.

## **Specific load airworthiness clearance and certification**

A possible sequence of rotorcraft ESL AWQ and specific load clearance is summarized in the schematic Fig 4, which is an extension of the Sikorsky methodology described in Ref 6. The process is as follows:





**Figure 4: Illustration of methodology for developing external sling load clearance envelopes.**

## Develop ESL simulation model

Approaches to developing and validating a suitable math model of the combined rotorcraft and ESL are described by Sikorsky in Ref 6, and Boeing in Ref 9.

## Define the ESL structural load envelope.

The ESL loadings that can be accommodated will depend on the rotorcraft's loading-c.g. envelope and the load capabilities of the ESL hook(s).

## Develop generic OFE

### Sling sets

Identify the sling sets to be used.

### For AWQ with single point suspension loads

Perform analysis and piloted simulation to determine flight envelopes where compliance can be shown with the three ESL airworthiness criteria. Verify these envelopes with flight tests of selected

ESL. If possible, develop envelopes for a set of generic loads that range from small high density to large low density. The selected density-size range should cover the range of expected loads that will be encountered in operational use.

### For AWQ with multi point suspension loads

Perform analysis and piloted simulation to determine flight envelopes where compliance can be shown with the three ESL airworthiness criteria. Verify these envelopes with flight tests of selected ESL. If possible, develop envelopes for a set of generic loads that range from small high density to large low density. Parameters beyond those considered for single point suspension loads must be analyzed to investigate the consequences of suspension system full or partial leg failure. Examples of such important additional parameters are the load pitch inertia, and the load planform and side areas.

## Generate specific load OFE

If the specific load is adequately represented within the generic load OFE, and for that load representation the ASE stability margins are not close to limits, the only additional testing required with the specific load would be to establish the load maneuvering envelope. This could be established during the load certification which would be performed by US Army Natick



RDEC in accordance with MIL-STD-913A. If there is any question regarding the ASE margins then the complete AWQ process should be carried out by the developer with the specific load. Even if the ASE margins appear robust, during the Natick tests the evaluation pilot shall verify the overall stability of all load configurations by disturbing the load with doublet control inputs in each axis at selected airspeeds through the certification range. Any tendency for vibrations or sustained oscillations to occur shall be referred to AMCOM for guidance. When performing the specific load certification, Natick shall refer back to AMCOM for guidance if it is proposed to use a sling set modified from that tested in the generic OFE development.

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## APPENDIX A. FLIGHT TEST TO ESTABLISH LOAD MANEUVERING ENVELOPE.

MIL-STD-913A (Ref 8) includes a flight test procedure to establish the maximum airspeed and maneuvering envelope that can be used with a load. The following part is recommended for use to supplement the ADS-33E-PRF MTE testing. The original MIL-STD-913A has been slightly modified as follows:

1. The rating criteria for flight characteristics of aircraft with external load has been omitted and replaced by the Cooper-Harper HQR scale. In addition, it should be clearly stated that the rating shall be of the pilot's ability to perform the task with the aircraft/load combination, not as in the MIL-STD-913A assessment criteria which requests the pilot to assess the effects of the load on the aircraft.
2. Additional checks are required to verify that the aeroservoelastic stability of the rotorcraft-load combination is satisfactory. To do this small control reversals (doublets) shall be applied to the pitch, roll, yaw and collective axes in turn, at each airspeed throughout the certification range. Any signs of vibrations or sustained oscillations within the clearance envelope should be reported to US Army Aviation and Missile Command (AMCOM) for further investigation.
3. Other minor changes are shown in the text. Additions to the original are shown underlined deletions are shown ~~striketrough~~.

### ~~Test plan for helicopter flight testing of external loads and the multi service flight data collection sheet~~

#### Test outline for ESL maneuvering envelope definition

The purpose of this phase of flight testing an external load is to determine the maximum stable Airspeed and any limitations to the flight envelope for the particular helicopter and load combination being tested. This is accomplished by operationally flight testing the load through a series of maneuvers and rating the aircraft response ~~to~~ with the external load and the response of the load itself for each maneuver.

**Warning.** This is an operational test. All maneuvers are to be performed within the standard operating parameters of the aircraft and crew. Aircraft performance limitations should never be exceeded

~~The Multi Service Flight Data Collection Sheet (FDCS) outlines the required maneuvers and is used to document flight testing. It~~ Flight testing is divided into four sections covering hover and transitional flight, straight and level flight, climbing/descending and turning flight ~~and summary of results.~~ In each section the maneuver being performed is rated by the pilot/copilot using the rating criteria for flight characteristics of aircraft with the external load Cooper-Harper HQR scale, and by the crew chief/aircrew observer using the rating criteria for characteristics of external load during flight (see attached). After ~~During~~ performing each maneuver rating and observing the effect of small control disturbances in each axis (pitch, roll, yaw and collective), the pilot/copilot calls out the maneuver and a rating, and the chief/aircrew observer responds with his/her rating. The consensus rating/Level is then recorded by the pilot/copilot ~~on the FDCS.~~

The durations, rates, angle of bank etc provided for the maneuvers ~~on the FDCS~~ are recommendations. If performance of a maneuver as outlined ~~on the FDCS~~ will exceed the performance limitations of the aircraft do not perform it. If possible, change the duration, rate, angle of bank, airspeed, etc so that it can be performed within the aircraft's performance limits.

In Section 1, Hover and transitional flight, the recommended duration of the maneuvers is 10 sec. As outlined above, while in steady flight and following small control disturbances in each axis (pitch, roll, yaw and collective) the pilot/copilot calls out the maneuver and a rating, and the crew chief/aircrew observer responds with his/her rating

After completing the Section 1 maneuvers, the helicopter carefully accelerates to the starting airspeed for Section 2, Straight and Level Flight. The starting Airspeed is determined in the pre flight brief based upon characteristics of the load being tested. Once the starting Airspeed is reached, and following small control disturbances in each axis (pitch, roll, yaw and collective) both the pilot/copilot and the crew chief/aircrew observer rate the load. The Airspeed is then incrementally increased until the maximum stable airspeed (Level 2) is determined by a consensus of the aircrew. Each airspeed (5 -10 KTAS increments are recommended) and its consensus rating is recorded on the FDCS. Maximum stable airspeed is defined by aircraft power limits, aerodynamic load instabilities, adverse aircraft response to the load, or tendency for vibrations or sustained oscillations.

In Section 3, Climbing/descending and turning maneuvers, the goal is to determine if any maneuver limitations exist at the maximum airspeed determined in section 2. ~~At the top of Section 3 the Airspeed, aircraft gross weight and the maximum authorized angle of bank are entered.~~ The angle of bank for the turning maneuver is incrementally increased up to angle of bank maximum if possible. If the turning maneuvers cannot be performed at any one of those bank angles due to load instability or other factors, record the actual maximum angle of bank ~~at the bottom of Section 2~~ and provide an explanation ~~on the reverse side~~. As in Sections 1 and 2, the pilot/copilot calls out the maneuver and a rating, and the crew chief/aircrew observer and replies with his/her rating. If at any time during performance of these maneuvers it is determined that the load is unstable or there is a tendency for vibrations or sustained oscillations at this airspeed, the airspeed should be decreased and the maneuvers repeated and rated at the new lower airspeed. If the climbing and descending maneuvers are performed at a rate less than 500 ft/min, provide an explanation ~~on the reverse side~~.

### **Rating criteria for characteristics of the external load during flight**

Level 1 (A) -Load maintains directional stability throughout maneuvers. Minimal load oscillation and/or minimal load rotation or weathervaning. Requires minimal concentration by the flight crew

Level 1 (B)-Load maintains directional stability for most maneuvers. Only moderate oscillation and/or moderate load rotation or weathervaning occurs. Requires minimal concentration by the flight crew.

Level 2 (C)-Load may oscillate, rotate or weathervane during most maneuvers. Directional orientation is not stable throughout maneuvers. However, the load remains stable in its rotational state and does not pose a threat to the aircraft.

Level 3 (D)-Load oscillates, rotates or weathervanes during all maneuvers. Directional instability may become severe and require immediate action by the flight crew to prevent danger to the load, aircraft, or personnel.

Worse than Level 3 (F)-Load is uncontrollable for most or all maneuvers. Directional instability is unpredictable and dangerous. Transport of the load at the prescribed Airspeed is not recommended.

## **Flight maneuvers**

### **Section 1: Hover and transitional flight**

Hover in ground effect (HIGE)  
Left turn on spot HIGE  
Right turn on spot HIGE  
Left slide, 10 deg bank HIGE  
Right slide 10 deg bank HIGE  
Hover out of ground effect (HOGE)  
Left turn on spot HOGE  
Right turn on spot HOGE  
Left slide, 10 deg bank HOGE  
Right slide 10 deg bank HOGE  
Transition to forward flight  
Transition from forward flight

### **Section 2: Straight and level flight (determine maximum stable airspeed)**

Airspeed increments

### **Section 3 climbing/descending and turning (at maximum stable airspeed)**

Straight climb  
Straight descent  
~~Pull-out standard rate~~  
~~Small control reversals, (all axes).~~

Coordinated level right turn 15 deg bank  
Coordinated level right turn 30 deg bank  
Coordinated level right turn maximum bank  
Climbing right turn, 30 deg bank, minimum 500 ft/min  
Climbing right turn, maximum bank, minimum 500 ft/min  
Descending right turn, 30 deg bank, minimum 500 ft/min  
Descending right turn, maximum bank, minimum 500 ft/min  
~~Pull-out standard rate~~

Coordinated level left turn 15 deg bank  
Coordinated level left turn 30 deg bank  
Coordinated level left turn maximum bank  
Climbing left turn, 30 deg bank, minimum 500 ft/min  
Climbing left turn, maximum bank, minimum 500 ft/min

Descending left turn, 30 deg bank, minimum 500 ft/min

Descending left turn, maximum bank, minimum 500 ft/min

~~Pull out standard rate~~

## APPENDIX B: ADS-33E-PRF TREATMENT OF FAILURES AND RELIABILITY

The following are the paragraphs from ADS-33E-PRF (Ref 1) related to the treatment of failures.

### 3.1.14 Rotorcraft Failures

When one or more Rotorcraft Failure States exist, a degradation in rotorcraft handling qualities is permitted. Two methods of assessment shall be used, the first relates the allowable degradation of handling qualities to the probability of encountering the failure, the second must consider specific failures to happen regardless of their probability.

#### 3.1.14.1 Allowable Levels based on probability

The first method involves the following procedure:

- a. Tabulate all rotorcraft Failure States.
- b. Determine the degree of handling qualities degradation associated with the transient for each Rotorcraft Failure State.
- c. Determine the degree of handling qualities degradation associated with the subsequent steady Rotorcraft Failure State.
- d. Calculate the probability of encountering each identified Rotorcraft Failure State per flight hour.
- e. Compute the total probabilities of encountering Level 2 and Level 3 flying qualities in the Operational and Service Flight Envelopes. (This total is the sum of the rate of each failure only if the failures are statistically independent.)

A degradation in Levels of handling qualities, due to the rotorcraft Failure States, is permitted only if the probability of encountering the degraded Level is sufficiently small. These probabilities shall be less than the values shown in Table II.

TABLE II. Levels for Rotorcraft Failure States

PROBABILITY OF ENCOUNTERING	WITHIN OPERATIONAL FLIGHT ENVELOPE	WITHIN SERVICE FLIGHT ENVELOPE
Level 2 after failure	$< 2.5 \times 10^{-3}$ per flight hr	
Level 3 after failure	$< 2.5 \times 10^{-5}$ per flight hr	$< 2.5 \times 10^{-3}$ per flight hr
Loss of control	$< 2.5 \times 10^{-7}$ per flight hour	

#### 3.1.14.2 Allowable Levels for Specific Failures

The second method assumes that certain failures or combinations of failures will occur regardless of their probability of failure. The contractor and procuring agency shall mutually agree on which Failure States shall be treated as "Specific Failures." The allowable Level of flying qualities for each Specific Failure will be specified by the procuring activity. Alternatively, the procuring

activity may specify specific piloting tasks and associated performance requirements in the Failure State. As a minimum, the failures in 3.7 shall be treated as Specific Failures.

#### **3.1.14.3 Rotorcraft Special Failure States**

Certain components, systems, or combinations thereof may have extremely remote probability of failure during a given flight. These failure probabilities may, in turn, be very difficult to predict with any degree of accuracy. Special Failure States of this type need not be considered in complying with the requirements of this section if justification for considering the Failure States as Special is submitted by the contractor and approved by the procuring activity.

#### **3.1.14.4 Transients following failures**

The transient following a failure or combination of flight control system failures shall be recoverable to a safe steady flight condition without exceptional piloting skill. Tests to define the transients for comparison with the values in Table III and the results shall be made available to the procuring activity. For rotorcraft without failure warning and cueing devices, the perturbations encountered shall not exceed the limits of Table III.

#### **3.1.14.5 Indication of failures**

Immediate and easily interpreted indications of failures shall be provided, if such failures require a change of strategy or crew action.

## APPENDIX C: RECOMMENDED ESL HANDLING QUALITIES DESIGN CRITERIA FOR LOW SPEED AND HOVER IN THE DEGRADED VISUAL ENVIRONMENT

The work described in Ref 7 has resulted in HQ criteria that may be used to analytically assess the overall response of the rotorcraft ESL on. The criteria apply to the following conditions:

Single point ESL operations

Hover and low speed

In the DVE with  $UCE > 1$ .

Load Mass Ratio  $m_L / m_{Total} \geq 0.33$

If the operational missions do not require carrying an external load in the DVE, or if the rotorcraft vision aid results in  $UCE=1$ , it is desirable, but not necessary, to meet these criteria.

Not meeting these criteria will result in handling qualities that are no worse than Level 2 with an externally slung load in the DVE, as long as the load-off handling qualities are Level 1. No Level 2-3 limit has been defined that is specifically due to external load.

These criteria are based on the assumption that the basic rotorcraft without an external load is Level 1. It is cautioned that the combination of not meeting these criteria, and a rotorcraft that is Level 2, load-off, will probably result in Level 3 handling qualities in the DVE.

### Dynamic response HQ criteria ESL on

For Level 1:

The horizontal translational rate bandwidths shall be as follows:

*Longitudinal*  $\omega_{BW_x} \geq 0.44 \text{ rad/sec}$

*Lateral*  $\omega_{BW_y} \geq 0.59 \text{ rad/sec}$

The frequency range of favorable load coupling shall be as follows:

*Longitudinal*  $\Delta\omega_{L_x} \geq 0.39 \text{ rad/sec}$

*Lateral*  $\Delta\omega_{L_y} \geq 0.73 \text{ rad/sec}$

There are four definitions of bandwidth for both the longitudinal and lateral axes, two based on phase margin and two based on gain margin. All of these must be greater than the values specified by the above criteria.

It is recognized that it may be difficult to obtain Bode plots of translational rate to cyclic response with sufficient accuracy and resolution to measure these parameters accurately.

Therefore, it is acceptable to use an analytically derived Bode plot if the math model used to generate the Bode plot has been shown to correlate with flight data for input-output responses other than the translational rate to cyclic.



## Definitions of the Criterion Parameters

$\omega_{BW_{\phi_1}}$  is defined as the lowest frequency at which the phase passes through  $-135$  degrees, as shown in Figure 5. If the phase margin does not decrease below 45 degrees at frequencies below  $\omega_L$ , set  $\omega_{BW_{\phi_1}} = \omega_L$ , the load coupling parameter, defined below.

$\omega_{BW_{\phi_2}}$  is defined as the first (lowest) crossover frequency that results when the pilot gain provides 45 degrees of phase margin ( $\phi = -135^\circ$ ) at the second crossover frequency as shown on Figure 6.

$\omega_{BW_{G1}}$  is defined as illustrated in Figure 7 and is calculated as follows.

1. Find the magnitude that occurs at the first (lowest) frequency where the phase equals  $-180$  degrees.
2. Find the lowest crossover frequency that occurs if the pilot reduces the gain calculated in step 1 by 50%. This is  $\omega_{BW_{G1}}$

Note that Figure 7 uses the lateral response as an example since it provides a clearer illustration of  $\omega_{BW_{G1}}$  than the longitudinal response.

$\omega_{BW_{G2}}$  is defined as illustrated in Figure 8. It is calculated the same as for  $\omega_{BW_{G1}}$  above except that the second (highest) frequency  $-180$  degree phase crossing is used in step 1.

$\Delta\omega_L$  the load coupling parameter is defined as the range of frequencies where the phase margin is equal to or greater than 45 degrees, as shown in Figure 5.

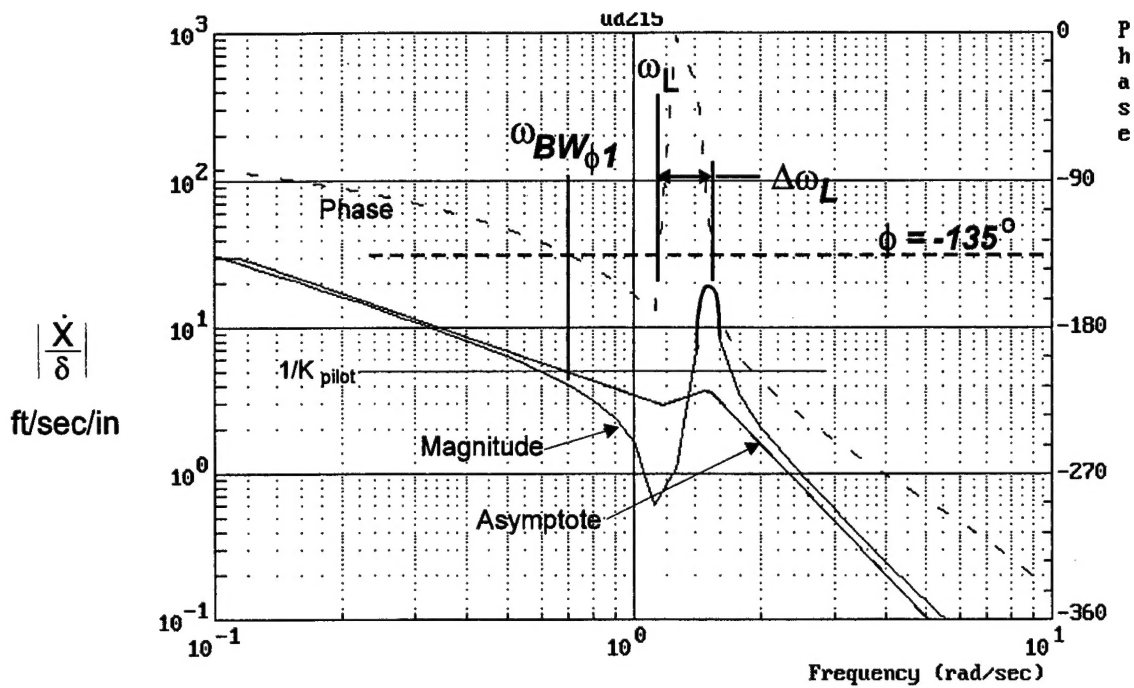


Figure 5 Definition of  $\omega_{BW\phi 1}$  and  $\Delta\omega_L$

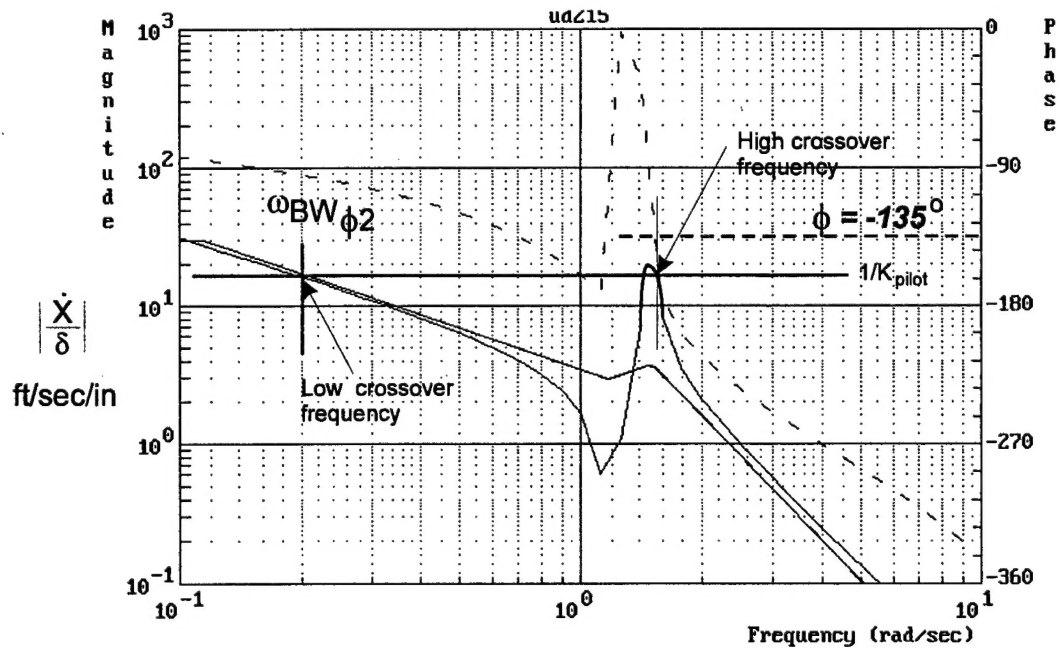


Figure 6 Definition of  $\omega_{BW\phi 2}$

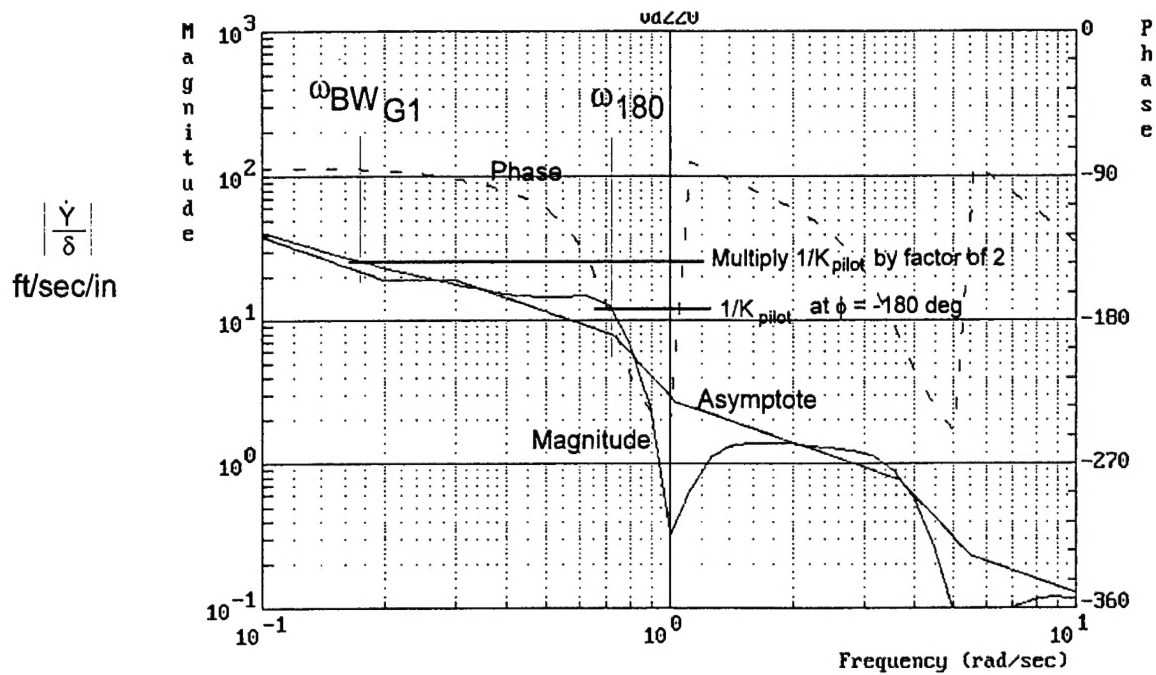


Figure 7 Definition of  $\omega_{BWG1}$

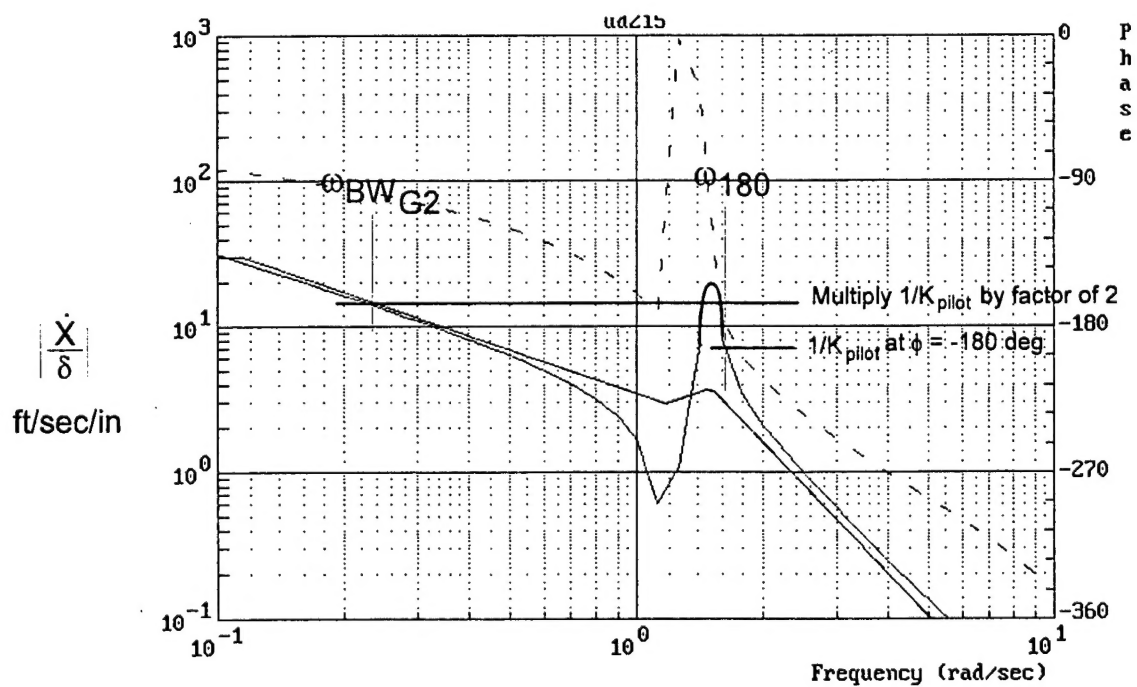


Figure 8 Definition of  $\omega_{BWG2}$

**REPORT DOCUMENTATION PAGE**Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

<b>1. AGENCY USE ONLY (Leave blank)</b>		<b>2. REPORT DATE</b> January 2002	<b>3. REPORT TYPE AND DATES COVERED</b> Contractor Report
<b>4. TITLE AND SUBTITLE</b> Airworthiness Qualification Criteria for Rotorcraft with External Sling Loads — Final Report Sept. 1999 - Nov. 2001			<b>5. FUNDING NUMBERS</b>  NAS2-14360
<b>6. AUTHOR(S)</b>  David L. Key			
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  Hoh Aeronautics, Vista Verde Center #217, 2075 Palos Verdes Drive N, Lomita, CA 90717, and Aeroflightdynamics Directorate, U.S. Army Aviation and Missile Command (AMRDEC), Ames Research Center, Moffett Field CA 94035			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  A-0207144
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>  U.S. Army Aviation and Missile Command, Redstone Arsenal, AL 35898-5000 and National Aeronautics and Space Administration Washington, DC 20546-0001			<b>10. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>  NASA/CR-2002-211390 AFDD/TR-02-A-002
<b>11. SUPPLEMENTARY NOTES</b> Point of Contact: David L. Key, Key Qualities, Oceanside, CA 92056 (760) 726-4632			
<b>12a. DISTRIBUTION/AVAILABILITY STATEMENT</b>  Unclassified — Unlimited Subject Category 08                      Distribution: Standard Availability: NASA CASI (301) 621-0390			<b>12b. DISTRIBUTION CODE</b>
<b>13. ABSTRACT (Maximum 200 words)</b>  This report presents the results of a study to develop airworthiness requirements for rotorcraft with external sling loads. The report starts with a review of the various phenomena that limit external sling load operations. Specifically discussed are the rotorcraft-load aeroservoelastic stability, load-on handling qualities, effects of automatic flight control system failure, load suspension system failure, and load stability at speed. Based on past experience and treatment of these phenomena, criteria are proposed to form a package for airworthiness qualification. The desired end objective is a set of operational flight envelopes for the rotorcraft with intended loads that can be provided to the user to guide operations in the field. The specific criteria proposed are parts of ADS-33E-PRF, MIL-F-9490D, and MIL-STD-913A all applied in the context of external sling loads. The study was performed for the Directorate of Engineering, U.S. Army Aviation and Missile Command (AMCOM), as part of the contract monitored by the Aeroflightdynamics Directorate, U.S. Army AMCOM.			
<b>14. SUBJECT TERMS</b>  Rotorcraft, External sling loads, Airworthiness, Handling qualities			<b>15. NUMBER OF PAGES</b> 33
			<b>16. PRICE CODE</b>
<b>17. SECURITY CLASSIFICATION OF REPORT</b> Unclassified	<b>18. SECURITY CLASSIFICATION OF THIS PAGE</b> Unclassified	<b>19. SECURITY CLASSIFICATION OF ABSTRACT</b> Unclassified	<b>20. LIMITATION OF ABSTRACT</b> UL